PB80-195423

Petroleum Hydrocarbons and Their Effects on Marine Organisms, Populations, Communities, and Ecosystems

(U.S.) Environmental Research Lab.
Narragansett, RI

1979

U.S. Department of Commerce
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1. REPORT NO.	2.	3. RECI
EPA-600/J-79-095	JOURNAL ARTICLE	PB80-195423

4. TITLE AND SUBTITLE
Petroleum Hydrocarbons and Their Effects on Marine Organisms, Populations, Communities, and Ecosystems

5. REPORT DATE

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
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8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Environmental Protection Agency
Environmental Research Laboratory
Narragansett, RI 02882

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS
SAME

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES In: Sources, Effects & Sinks of Hydrocarbons in the Aquatic Environment, Proceedings of Symposium, American University, Washington, DC, August 9-11 1979 pp. 464-504

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Strict control is suggested for oil development and related activities in certain shallow, highly productive, continental shelf regions, and in relatively confined, ecologically important wetlands and estuaries. Soft-bottom, coastal benthic communities are vulnerable to impact, and recovery from spilled oil could be relatively slow where oil tends to persist or where community stability is extremely low. Bird populations are highly susceptible to lethal and adverse effects, if contact with oil occurs. Local breeding populations of many organisms (including ichthyoplankton and meroplankton) may become heavily impacted, especially in certain confined coastal areas. In general, populations and/or communities of pelagic fish, mammals, phytoplankton, and zooplankton are considered low risk in terms of susceptibility to effects of petroleum. Little is known of the ecological effects of petroleum on neuston or in coral and polar ecosystems.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Oil pollution, Environmental effects, Oil Spills, Water Pollution effects, Aquatic ecosystems, Marine environments		

REPRODUCED BY
NATIONAL TECHNICAL INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release Unlimited	20. SECURITY CLASS *(This page)*	22. PRICE

EPA-600/J-79-095
JOURNAL ARTICLE

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to effects of petroleum. Little is known of the ecological effects of petroleum on neuston or in coral and polar ecosystems.

INTRODUCTION

In recent years marine scientists have shown a greater concern for the impact of petroleum and petroleum products on the health of the world's oceans and coastal areas. The words "Torrey Canyon" and "Santa Barbara," together with Thor Heyerdahl's observations of tar balls and slicks in the open Atlantic have heightened the awareness of the American public as well as its scientific community on the possible impact of petroleum products on marine life. This concern seems to be somewhat warranted in view of America's growing dependence on petroleum products--the average U. S. citizen utilizes some 7,800 gallons of petroleum per year--and the consequent demand for offshore oil development and related nearshore activities centered around transportation and processing.

Arriving from a host of sources, much of this petroleum ultimately finds its way to the marine environment (Table 1). Approximately 16% of the total amount spilled is introduced naturally or accidentally. However, by far, the largest percentage of petroleum is introduced as a result of intentional discharges which are capable of being regulated through government policy. With increasing supply and demand, an increase in the rate of petroleum pollution is inevitable, unless such regulations exist.

The determination of a permissible level of petroleum contaminants in the marine environment should be based foremost on careful consideration of their potential impact to vulnerable and sensitive marine life forms. It is the purpose of this paper to review and synthesize available data, and provide an up-to-date summary of the ecological effects of petroleum and petroleum products on marine life, from single organisms to intact ecosystems.

EFFECT OF PETROLEUM ON MARINE ORGANISMS

Marine toxicology is a science in its infancy. As a result, many of the earlier attempts to determine the toxic potential of petroleum and petroleum products to marine life have produced confusing and often erroneous conclusions. For example, lack of standardized techniques with respect to type of oil, test organism, or duration of exposure has introduced much confusion in the interpretation of reported effects. In addition, bioassays have been performed in the laboratory under static conditions, with little attempt made to simulate natural conditions which influence the behavior of the test organisms. Rarely were analytical techniques employed to measure the

exact amount of oil in solution. Instead, investigators reported the amount of oil initially added to aquaria on a volume to volume basis. Hence, concentrations causing biological effects were often over-estimated.

Death has often been used as a measure of biological response and has been reported in a form such as the LD-50, i.e., the concentration of oil responsible for the death of 50 percent of the test population over a given time period. The literature is replete with references to such values (see review in Moore et al.[1]). Too often these LD-50 values were calculated for resistant species that were easy to manage in the laboratory, while fragile species were often excluded from studies. Obviously, "safe" levels of oil contamination for all marine organisms lie well below the LD-50 values calculated for tolerant species.

The authors of recent reviews[1,2,3,4,5] on the subject of oil pollution have synthesized much of this fragmentary information, and as a result a great deal more has been learned concerning types of biological responses at the organism level and the fractions of oil responsible for such effects. Accordingly, Moore[2] has identified five major categories of effects from oil on individual organisms: 1) direct lethal toxicity; 2) sublethal disruption of physiological or behavioral activities; 3) the effects of direct coating by oil; 4) incorporation of hydrocarbons in organisms which may cause tainting of edible species and/or accumulation of potentially carcinogenic polycyclic aromatic hydrocarbons in food chains; and 5) changes in biological habitats.

Lethal toxicity refers to interference with subcellular, cellular, and physiological processes (e.g., disruption of membrane activities) leading directly to organism death.[2] As a result of the literature evaluation by Moore et al.[1] and their analysis of the type of compounds causing toxicity in variously reported bioassays, it was determined that soluble aromatic hydrocarbon derivatives (mono- and dicyclic aromatics, and naptheno-aromatics) are the primary cause of organism mortality. Low molecular weight paraffins can cause narcosis, while certain heterocyclic compounds are lethally toxic; but concentrations capable of causing such responses are extremely high and are unlikely to result from oil spills.[2,6]

Table 2, which was adopted with modifications from Moore et al.[1] and Moore,[2] summarizes the minimum concentrations of soluble aromatic hydrocarbon derivatives (S.A.D.) necessary to cause lethal toxicity for a wide variety of marine organisms. Minimum lethal concentrations for particular categories of organisms are based on Moore et al.[1] estimates of S.A.D. in solution from relevant bioassays that were reported in the literature. The factor of ten uncertainty observed for each category of organisms in Table 2 is a result of the confusion created when interpreting results from such a large number of bioassays performed prior to the development of standardized techniques. Table 2 also reveals estimated maximum percent S.A.D. for several types of petroleum products. Thus, refined products such as No. 2 Fuel oil,

which contain a high content of S.A.D., are considerably more toxic than equal amounts of crude oil or residual products.

Apparently, lethal effects of S.A.D. appear at the 1 to 100 part per million range for the adult forms of most marine organisms. Crustaceans and certain benthic organisms, especially burrowers, are the most sensitive (1 to 10 ppm), while fish and bivalves are moderately sensitive (5 to 50 ppm), and gastropods and marine flora the least sensitive (10 to 100 ppm). Lethal toxicity from S.A.D. may occur at lower concentrations, 0.1 to 1 ppm, for the more sensitive larval and possibly juvenile life stages.

Sublethal effects result from cellular and physiological interferences, usually leading to some form of abnormal behavior, particularly disruption of normal feeding and reproductive patterns.[2] Such behavior is often dependent upon sensitive levels of communication via chemical cues, which may be disrupted by very low levels of petroleum hydrocarbons in solution. Sublethal responses may indirectly result in lethal effects. Table 3, which was adopted with updated modifications from the National Academy of Sciences,[5] summarizes sublethal effects of petroleum on marine organisms. From this synthesis, it is apparent that many organisms respond to sublethal effects of S.A.D. in the part per billion range, particularly between 10 and 100 ppb. However, several citations from Table 3 reveal sublethal responses in the low part per billion range, i.e., 1-10 ppb. Included are a wide variety of effects across animal and plant kingdoms and components thereof. Such effects include: delaying cellular division in phytoplankton;[7] producing abnormal fish spawn;[8] reducing chemotactic feeding responses in snails[9] and in crabs;[10] inhibiting mating responses of male crabs to sex pheromones;[10] decreasing filter feeding activity of mussels;[11] and decreasing survival and fecundity in worms.[12] The ecological implications, as well as the exact mechanisms causing sublethal responses are still poorly understood.

The effects of direct coating of oil include disruption of physiological or behavioral processes, resulting from smothering, entanglement of appendages or filtering devices, and dislodgement of sessile organisms from their substrates.[1,2,3,4] Residual oil fractions are implicated as the primary cause of such effects. The effects of direct coating are most significant along exposed shorelines populated by attached or relatively immobile species (barnacles, mussels, limpets, snails, algae, etc.).

Incorporation of petroleum hydrocarbons in marine organisms may result in tainting of edible species and/or accumulation of potentially carcinogenic polycyclic aromatic fractions into marine food chains.[2] Exposure of some animals, particularly filter feeding bivalves and fish, to as little as 1 ppb dissolved petroleum hydrocarbons can result in tainting.[2] Humans can taste petroleum hydrocarbons in animal tissue at concentrations between 5 and 50 ppm.[2,13] The belief that oil can induce cancer in marine organisms is based on the following reasoning: 1) polycyclic aromatic hydrocarbons have been identified as

carcinogenic agents; 2) they are widely distributed over the ocean; 3) they are found in the residual fractions of crude oil; and 4) they have been found to concentrate in animal tissues.[2] Incidence of cancer has been evidenced among clams sampled from oil spill sites.[14,15] However, there has been no conclusive evidence to date positively implicating oil as the direct cause of the observed neoplasms.

Much of the oil spilled in the marine environment ultimately finds its way to bottom sediments. As a result, bottom habitats are potentially subject to alterations in their chemical and/or physical integrity. Benthic organisms are highly dependent on such integrity. To fully understand the effects of these alterations, one must search beyond the organism level of response for shifts in species composition and distribution, functional community changes, etc.

EFFECT OF PETROLEUM ON MARINE POPULATIONS, COMMUNITIES, AND ECOSYSTEMS

As demonstrated in Tables 2 and 3, individual organisms are killed by soluble oil fractions in the 0.1 to 100 part per million range, and may exhibit sublethal responses at very low concentrations (1 to 10 ppb). However, the ecological significance of these responses are manifested only by consideration at or above the population level of biological organization. As expressed by the U. S. Council on Environmental Quality,[16] an individual organism may be proven extremely sensitive to oil in the laboratory; but under natural conditions, due to effective reproductive and dispersal strategies, or high rates of birth, maturation and immigration, an entire population may recuperate rapidly from a catastrophe. Similarly, the expected rapid recovery of a community of organisms proven resistant in the laboratory may be seriously delayed under natural conditions as a result of restrainable interactions, i.e., competition for food and space, dependence on a specific food source, or the ability to compete with other recovering species.

To better visualize the impact of a stress on a system as a complex as a total aquatic ecosystem, one might imagine the latter as a giant, delicately balanced artist's mobile. The mobile, similar to an ecosystem, has both hidden, functional balance and visible structure (the weighted components). Small perturbations may momentarily set the weighted components into motion. However, if the system is well balanced, i.e., stable, fluctuations gradually lessen until the original state of equilibrium is reached. It is possible for several components, each serving as another's counterbalance, to be removed simultaneously with little or no change in the system's stable configuration. Yet, if just one strategically positioned component is removed, stability may be lost, and the original state of equilibrium may never be regained.

"Stability" seems to be the key word. It is the ability of a system to maintain or return to its initial state after an external

perturbation.[17,18] Determining the stability of a system then helps one to predict its susceptibility and long-term behavior in response to perturbations. Of course, the behavior of a natural system to a perturbation (such as oil) is dependent on factors other than the system's stability, for example the persistence of the perturbation, etc. Boesch[18] describes stability as being dependent upon "resistance," the ability to withstand stress without change, and "resiliency," the speed at which the system returns to a state of equilibrium following the perturbation.

Many aquatic ecologists believe that communities subjected historically to a constancy of abiotic factors (temperature, salinity, oxygen, etc.) have developed through time the most extreme, complex biological interactions.[19,20] Member species have become highly specialized, contributing to speciation. The resulting communities are "biologically accommodated" and are characterized by a high diversity of species. In contrast, communities subjected to rigorous and variable abiotic factors (fluctuating temperatures, salinities, or periods of light and darkness; atmospheric exposure; breaking surf; etc.) may be more controlled by their physical environment. They are composed of a relatively few eurytolerant species and are characterized by low diversity.

According to Copeland,[21] and supported by Boesch,[18] those systems already accustomed to "energy requiring stresses" (low diversity systems) are better able to resist additional human disturbances, e.g., petroleum, than those adapted to relatively constant environments (high diversity systems). This hypothesis contradicts the earlier belief[22,23] that the more complex a community (i.e., the more numerous its species and the more intricate their interrelationships), the more stable it is. The earlier hypothesis was based on the assumption that effects of stress in complex communities would be buffered, since many alternate sources of food and/or community strategies would be available. Which hypothesis is correct remains to be proven.

Other than hypotheses, we now have very little first-hand information of how various populations, communities, or ecosystems respond to oil contamination. What little is known has been learned from post-spill studies, surveys of chronically polluted areas, or from the few experimental field studies involving artificial oiling of natural or simulated "ecosystems." Interpretation of results from the former two methods has been gravely limited due to the lack of precise pre-spill control information to use for comparison. The experimental field approach is recommended since it corrects for the limitation memtioned above and still emphasizes the importance of natural environmental and biological variables in influencing the behavior of both the oil and the subjected communities. For a review of studies following major spills, see National Academy of Sciences.[5]

Damages from oil contamination result from either single spills or from low-level continuous discharges. In the spill situation, the exposed community will often experience an initial impact, the extent

of which depends largely on conditions of the exposure--amount of oil, type, degree of weathering prior to exposure, degree of spreading, cleanup techniques, and the resistance of the organisms. Less resistant individuals may die, usually as a result of chemical poisoning or complications from direct, physical coating--suffocation, entanglement or dislodgement.[4] Changes in population densities, age-distribution and species abundance and distribution may result from initial mortalities. Shifts in the relative sizes of interacting populations may also occur, favoring an increase in some as a result of relaxed pressures in the absence of others. The latter is exemplified by the increases in algal populations in some contaminated areas, resulting from the disappearance of grazers[24,25,26] and the invasion of oil-devastated areas by opportunistic polychaetes.[27,28] Oil may also alter the physical or chemical integrity of the habitat,[16] making it undesirable for recolonization and thus delaying recovery.

Results gathered thus far have revealed that marine communities subjected to oil spills are able to recover, although the time required has ranged from weeks for rocky shores at Santa Barbara[29] to several years for soft-bottom, offshore and marsh communities at West Falmouth.[30]

The rate of recovery depends on the extent of the initial impact; the persistence of the oil; and inherent factors of the community governing its resiliency (effectiveness of reproductive and dispersal strategies in replenishing numbers), and the extent of biological interactions such as predation, parasitism, competition and commensalism.[4,16] Recovery is usually thought to be complete if the internal dynamics of each population--density and stable age distribution (structure)--and the species interactions (function) have been restored to pre-spill levels.[16]

Continuous, low-level contamination results from frequent exposure to oily waste discharges from refineries, sewage treatment facilities, oil ports, petrochemical plants, etc.; or from exposure to persistent oil fractions left over from a spill. In such cases, initial impacts are not as significant as the gradual structural or functional changes which develop through time. This has been exemplified by the effects of persistent oil following the West Falmouth spill,[27,28,30,31] pollution from (oily) wastes in Los Angeles Harbor,[32,33] and pollution from refinery effluents in Milford Haven, England.[34]

For management purposes, it is extremely important for decision makers to understand how stable various types of marine systems are in response to oil. Such information can be used to help predict the ecological impact of an oil-related operation while it is still in the planning stages. Unfortunately, there is too little known presently to make definitive conclusions for every system type. Nonetheless, an attempt is made herein to review on a broad scale what little is known, or what can be theoretically expected in terms of responses to initial impact and rates of recovery. Estimates for recovery are often conjectural. Accordingly, Table 4 summarizes the responses of marine populations and communities to oil, while Table 5

summarizes the responses of some major ecosystems to the effects of oil.

Effect of Petroleum on Marine Populations and Communities

Plankton.--The "passively"drifting plankton appear to be threatened primarily by the chance event of contacting a floating slick. Individuals may die from chemical poisoning within the toxic plume, or as a result of complications from physical coating by the slick itself. The consequent loss of large populations could have a local effect on productivity.

Generally, however, dramatic changes in plankton as a result of oil contamination have not been observed. Smith[35] observed minor population changes in the ichthyoplankton and phytoplankton following the Torrey Canyon spill, but in general the plankton were apparently unaffected. Likewise, no apparent changes in phytoplankton or ichthyoplankton were reported following the Santa Barbara blowout.[29,36] Furthermore, zooplankton were found to be unaffected by brine effluents from oil fields in Texas estuaries.[37]

It must be pointed out that plankton populations are usually characterized by wide spatial and temporal variations. This has made it extremely difficult to discern effects from spills, where precise control or prespill information has not been available. However, using the experimental, field approach, an interesting effect was observed in an artificially oiled, natural marsh community.[38] Here, the application of crude oil caused an initial decrease in zooplankton, accompanied by massive phytoplankton blooms. As the oil began to disappear, zooplankton rapidly increased in response to the availability of food.

With exceptions, the recovery of phytoplankton and zooplankton communities, particularly in large bodies of water, is apparently rapid. These species are widely dispersed, reproduce rapidly and grow quickly to maturity, such that pre-spill population densities and/or stable age-distributions are soon restored.[16] However, in estuarine nursery grounds or other confined areas small localized breeding populations--particularly the larval forms of some fish (ichthyoplankton), or crustaceans and molluscs (meroplankton)--may become severely impacted, and complete recovery may take several years.[16]

Neuston.--Little is known of the ecological effects of oil on neuston, assemblages of organisms living at or near the surface of the sea. Yet, much concern has been voiced for these unique communities since they appear as being quite vulnerable to contact with either a floating slick or ubiquitous tar lumps. Burns and Teal[39] have reported the contamination of pelagic Sargassum communities with petroleum hydrocarbons in the central North Atlantic. However, study of the possible ecological effects of oil was not considered.

Since the ecology of neustonic communities is poorly understood and

case studies of oil impact are rare, it is difficult to predict their recovery rates.

Benthos.--In comparison to pelagic communities (plankton and most fish), benthic communities are particularly vulnerable to impact of spilled oil, since bottom substrates accumulate oil and since many of the species (represented largely by attached plants and small invertebrates living in or on the substrate) are sessile or relatively immobile and hence cannot escape the pollution. Initial damages from oil have been reported on rocky shores,[26,29,35,40,41] along soft-bottom intertidal shores,[42,43,44,45] and in subtidal substrates.[26,27,35,44]

As Boesch et al.[4] have pointed out, mortalities have resulted from chemical poisoning (e.g., Tampico Maru and West Falmouth spills) or from the effects of physical coating, such as loss of purchase on substrates or suffocation (e.g., Santa Barbara and San Francisco Bay spills). The loss of individuals may result in decreases in densities or changes in age distributions within populations, or changes in the abundance and distribution of species.

On several occasions oil was reported to have affected the functional relationships between different, interacting species. For example, after the Tampico Maru spill, extensive kelp beds developed in the absence of grazing abalones and sea urchins, which normally kept the sporelings in check.[26] Following the Torrey Canyon spill, once grazing limpets and periwinkles were killed by a combination of the oil and toxic emulsifiers, dense growths of green algae developed, followed by brown rockweeds.[24,25] Similarly, under temporary noncompetitive conditions, the opportunistic polychaete, Capitella capitata, invaded oil-devastated areas following the West Falmouth spill.[27,28] Additionally, Clark et al.[46] reasoned that normally occurring anemones were few in number along a rocky shore exposed to an oil spill in Wreck Cove, Washington, since algae, as evidenced by their abundance, had outcompeted the former for space.

Rates of recovery for oil-impacted benthic communities have ranged from weeks on rocky shores at Santa Barbara[29] to half a decade in soft-bottom, offshore and marsh stations at West Falmouth.[30] With exception (Tampico Maru spill), intertidal communities appear to have been affected the least and to have recovered the fastest--usually within two years.[4] As Boesch et al. point out, rapid recovery occurs since: 1) all but the most resistant fractions of oil are quickly removed by waves, reducing chronic stress, 2) the species reproduce rapidly to replenish what is lost, and 3) the species generally have acquired mechanisms for protection which increases resistance and minimizes the initial impact.[4]

The recovery rates for soft-bottom, intertidal communities may be slower than for their rocky counterparts, since in the case of the former, the oil may persist for longer periods of time in the unconsolidated substrate. Energy from waves breaking along a beach will

aid in removing oil-laden sediments from a sandy or muddy beach; however, in such an event the pollution is only relocated to an offshore area.

In comparison to intertidal communities, full recovery has been extremely slow for some subtidal communities (e.g., West Falmouth). This is largely due to the oil's persistence once incorporated into the subtidal sediments. Here, the oil may remain for long periods of time relatively free from bacterial attack or mechanical dispersion. In addition, it is possible that many subtidal communities are not as stable--resistant or resilient--as communities which have adapted to the extremely variable and rigorous conditions found in intertidal areas. Of course, it is recognized that one may find stable as well as unstable subtidal communities, and rates of recovery will be faster or slower depending on their degree of stability. Yet, for now, it is convenient to conjecture that in comparison to some other broad categories reviewed herein, subtidal communities require relatively longer recovery periods.

Benthic communities have also exhibited changes in response to chronic low-level inputs of oil. For example, Crapp[34] noted that in areas around refinery outfalls in Milford Haven, fucoid algae were more abundant than molluscs, which normally graze upon the algae, while in unpolluted areas the molluscs were more abundant. Similarly, Reish[32,33] surveyed sections of Los Angeles Harbor which were apparently receiving refinery wastes and found an absence of species, except for the very resistant polychaete, Capitella capitata. When Los Angeles refineries ceased discharging wastes, the diversity of species increased in previously uninhabited areas.

Fish.--In many cases, fish have the ability to avoid an oil-impacted area,[4,26] particularly if the area is not restricted in size (e.g., in offshore waters). Some fish kills have been reported following major spills--Argea Prima[47] spill and the West Falmouth spill[44]--or in artificially oiled ponds.[38,48] However, generally the oil has been confined to relatively small and shallow bodies of water, so that exposures were assured. Boesch et al.[4] pointed out that fishes may be more resistant than other organisms to the toxic effects of oil, since their surfaces are coated with oil repellent mucous.

In general, populations of pelagic fishes, that are by chance affected by a spill, will probably recover quickly since larval and adult immigrants will rapidly replace individuals that were eliminated. Benthic fishes may be threatened if oil should accumulate in bottom sediments at levels capable of inducing sublethal or lethal responses. Apparently the greatest threat is to local breeding populations which congregate in small spawning and nursery grounds. In such a case, there is a greater chance for exposure since the grounds are often represented by relatively narrow waterways. Furthermore, the larval stages are particularly sensitive to chemical poisoning. If a local population is reduced it may take years to recover.

Birds.--Some populations of sea birds, including the auks, penguins and diving ducks, are particularly threatened by oil spills.[5] For example, since many are flightless (or weak fliers) and dive to collect their food or to avoid a disturbance, their chances of contacting a slick are increased. They are also highly gregarious--which means that there is potential for a small local population to be lost all at once. Some species are extremely rare or near extinction and local losses may have an impact on the entire species.

Bird kills were reported following the Torrey Canyon spill, Southwest England;[35] the Esso Essen spill, South Africa;[49] the Santa Barbara spill, California;[29] the San Francisco Bay spill, California;[41] and on several other occasions.[5,50] Causes of death include: 1) disruption of feather surfaces leading to either drowning as a result of the loss of buoyancy, or pneumonia as a result of the loss of thermal insulation; 2) ingestion of toxic oil droplets from excessive preening; and 3) "accelerated starvation" as a result of increased metabolic activity (to compensate for loss of body heat) coupled with a decrease in feeding.[4]

Since birds are relatively long-lived and are not very prolific, replenishment of losses is often extremely difficult.[16] Recovery could be a very slow process.

Marine Mammals.--Despite much publicity and over-reactions from humans, it appears that oil has not caused serious effects on entire populations of marine mammals. In comparison to other animals, marine mammals are not particularly abundant. Hence, contact with oil occurs rather infrequently. Also, throughout most of the year many mammals are quite mobile and thus are apparently capable of avoiding heavily polluted areas. A breeding population of seals on an oiled beach represents an obvious exception, as well as small fur bearers living in coastal wetlands chronically polluted with oil.

Although incidents of oiling have been reported,[3] conclusive evidence of individual mortalities due to oil pollution is rare, if not lacking entirely. Possible harmful effects, however, include ingestion of toxic oil droplets during grooming; loss of thermal insulation and/or waterproofing as a result of coating; and irritation of eyes and exposed mucous membranes.[3,4] Eye irritations were reported after the Arrow spill[51] and after a spill of diesel oil off Alaska.[52]

If an entire population (conceivably a small breeding population on or near an oiled beach) were lost, then recovery could be a very slow process. Individuals are long-lived and are not extremely prolific. Also, the number of reproductive events per given time period can be small since breeding occurs rather infrequently and is often dependent upon complicated behavior. However, there is no supportive evidence for population losses as a result of oil pollution. On the contrary, oiled individuals among a population of elephant-seal pups on San Miguel Island survived and later dispersed in a normal manner.[53]

Effect of Petroleum on Marine Ecosystems

Open Oceans.--Researchers have in the past concentrated on studying effects of oil in coastal or inland regions, mainly as a result of their vulnerability to spilled oil and their biological or economic significances. Consequently, the ecological effects of oil in the open ocean is poorly understood. Yet, based on what little is known, it is felt that some general conclusions can be drawn.

For the most part, catastrophic effects are not expected in the open ocean environment, primarily as a result of the rapid dispersion and degradation of the oil, and the general low vulnerability of open ocean organisms to contact with oil. For example, damages to small populations of phyto- and zooplankton depend mostly on the chance event of encountering a floating slick. Individuals that do encounter the slick may be eliminated; however, once contact occurs and organisms are killed, numbers are generally quickly restored as a result of fast rates of reproduction and immigration. Adult pelagic fish are generally capable of avoiding a spill although they may ingest toxic oil droplets. It is not likely that dispersed oil would accumulate in open ocean sediments at levels toxic to benthic organisms, since oil would lose much of its toxicity before reaching the bottom.[16]

On the other hand, some communities, particularly the surface-dwelling neuston, are obviously threatened by contamination from floating oil. It is significant that floating tar lumps have been found along vast stretches of the ocean's surface.[54]

Outer Continental Shelf (OCS).--Concern for potential environmental impact has been expressed for certain OCS areas in the Atlantic and Gulf of Alaska, which are now being considered for the development of oil and gas resources. For example, the U. S. Council on Environmental Quality (CEQ)[16] has reported that high environmental risk is involved in the development of Northern Baltimore Canyon, Southwest Georgia Embayment, and the Gulf of Alaska; although less risk is involved in the development of Central and Southern Baltimore Canyon and George's Bank. It must be noted that CEQ's ranking of OCS environmental risks is based primarily on the probability of oil spills reaching the shore and impacting biologically productive coastal wetlands and estuaries or intensively used recreational beaches, rather than on potentially damaging effects that the oil may have on offshore communities. This illustrates the fact that very little is known of the ecological effects of disturbances in offshore, OCS areas.

Based on what little is known, some generalities have been drawn.[16] First, the impact of oil on entire planktonic populations should be slight, although fractions thereof might be eliminated as a result of coating or exposure to the toxic wake of a slick. Rapid recovery--within the life spans of the individual organisms--occurs since once the oil has dispersed, reinvading individuals from unaffected

neighboring areas are generally sufficiently numerous to restore population densities to prespill levels, and since individuals reproduce and grow to maturity rather rapidly. However, extreme caution must be exercised in developing certain OCS areas (e.g., Georges Bank) that are frequented by breeding and migratory populations of commercially or ecologically important species. Whole year classes of organisms may be affected by oil spills or by chronic lethal exposures, which may jeopardize the strength of the overall stocks.

Benthic communities in OCS areas may be moderately affected if oil reaches the bottom. It is conceivable that in most offshore areas oil would not accumulate in bottom sediments at levels high enough to cause dramatic alterations in the structure or functioning of the communities existing there. Much of the oil from an offshore spill is widely dispersed and somewhat detoxicated before reaching the bottom, such that it is not likely that any given area would become heavily coated with extremely toxic oil fractions. However, again, in shallow OCS areas (such as Georges Bank) low levels of soluble oil fractions could cause tainting of commercial shellfish or affect the behavior of certain commercially or ecologically important species.[11,56,57]

Moderate rates of recovery are expected for benthic communities in the OCS areas, and is dependent largely on the persistence of the oil once incorporated in the soft substrates. CEQ predicts a two to three year recovery period for sandy offshore substrates, and longer periods for substrates containing larger proportions of silt or mud.[16]

The CEQ report concludes that many populations of fish living in OCS areas are generally not threatened from spills, since they are free to move about and thus can usually avoid the oil. However, certain OCS fishes that migrate inland to breed and spawn--alewife, striped bass, salmon--may be threatened by nearshore spills, which could interrupt spawning migrations, disrupt complex breeding behavior, or affect sensitive larval forms aggregated in their nursery grounds. According to CEQ, some short-lived species such as pink salmon, which have a two-year life span, if subjected to severe losses in a given larval class, may in turn suffer significant losses in terms of population densities for the overall stock, and require a few years to recover. Longer-lived species can apparently sustain the loss of an entire year class without serious stock reduction. Studies to delineate temporal and spatial patterns for breeding and larval populations of OCS fishes are urgently needed to assess the potential impact of petroleum development in these areas.

According to CEQ, those species of fish considered potentially most vulnerable to OCS-related oil spills include: 1) winter flounder, sand lance, mummichog, alewife, and salmon for the Northern New England area (Maine to Cape Cod); 2) summer and winter flounder, tautog, sand lance, anadromous smelt, alewife, and striped bass for the Southern New England area (Cape Cod to Sandy Hook); 3) hogchoker and summer flounder for the Middle and South Atlantic area (Sandy Hook to Cape Canaveral); and 4) breeding populations of several salmon and

groundfish species in the Gulf of Alaska.

Open Estuarine Areas, Bays, Channels, Harbors.--The effect of petroleum and petroleum byproducts on open estuarine areas, bays, channels, and harbors deserve considerable attention, since these areas continue to serve as depositories for oily substances from a host of sources--boat traffic, tanker on- and off-loading practices, refineries, sewage treatment outfalls, accidental spillage due to collision or grounding, etc. Farrington and Quinn[58] reported that bottom sediments in the upper part of Narragansett Bay, Rhode Island, which receive large inputs from sewage treatment plants, tanker off-loading practices near oil storage points, and general boat traffic, are polluted with oil at concentrations ranging from 800 to 3,560 ppm (dry weight).

In such chronically polluted areas oil may gradually reduce the size of some populations of fish and benthic species, and induce changes in species abundance and distribution. This is exemplified by the observations of Reish[32,33] where he noted an absence of normally occurring benthic species near refinery outfalls and an overabundance of the very resistant, opportunistic polychaete, Capitella capitata. Single spills may cause similar effects, especially where the oil has a tendency to persist in subtidal sediments, prolonging the toxic effects (e.g., West Falmouth spill). The oil spilled at West Falmouth, as well as in Chedabucto Bay, Canada, persisted for several years. Oil spilled in Casco Bay and Muscongus Bay, Maine, has persisted for 11 years.[59]

Spilled oil may have a particularly significant impact on small, local breeding populations, especially fish and shellfish, which characteristically migrate in and out of these rather confined coastal areas. As noted earlier, larval and possibly juvenile forms are quite vulnerable to the toxic effects of oil. In this respect, the immediate impact of a major oil spill will depend largely on the time of year, i.e., whether animals have migrated to these areas and are breeding or spawning.

Recovery from spills in these areas is dependent on flushing characteristics of the body of water; shoreline characteristics, i.e., how consolidated the sediments are, wave exposure, or how confined the areas are as a result of the shoreline contour; routes of oil to benthos; and how stable the communities are against disturbances. In regard to the latter, Boesch[18] has found that, depending on the constancy and level of salinity, bottom communities from some portions of estuaries are more stable in response to disturbances than from other areas. For example, he characterized subtidal benthic communities appearing in polyhaline portions of a temperate estuary as being more diverse and less stable in response to disturbances than those communities found in mesohaline and oligohaline portions of the estuary. The latter are usually composed of relatively few species with wide physiological tolerances. Similarly, with regard to constancy in temperature, some tropical estuarine communities (which experience

little variation in other physical parameters as well) may be less stable in response to disturbances than temperate estuarine communities composed of species which have developed defensive mechanisms to cope with natural seasonal variations.[21]

Recovery may be a slow process for a local breeding population of fish or shellfish impacted by oil. Where individual year classes are heavily impacted, several years may be required to numerically restore the overall stock to prespill levels.

Wetlands.--An oil spill may have a significant impact on a wetland, e.g., salt marshes in temperate regions or mangrove swamps in the tropics. In the first place, these areas are extremely important biological resources. They are highly productive; form the basis of detrital food chains; provide habitat, breeding, and nursery grounds for fish and wildlife; act as sediment and nutrient traps; and serve as the important transition between terrestrial and marine systems.

Secondly, these shallow estuarine environments are particularly vulnerable to spills, as they are unquestionably subjected to a large amount of oil-related activities. Also, once spilled the oil has a good chance of reaching either the shore or bottom, since wetlands are typically shallow and confined by their shape and size. Oil which has not washed ashore, may be deposited in subtidal sediments via particulate matter, and may remain there, under typical anaerobic conditions, for long periods of time. Also, oil has a tendency to coat oleophilic detritus which may then be ingested by detritivores.[4]

Several post-spill reports illustrate detrimental effects of oil spilled in wetland environments. For example, damages to mangrove communities were reported following the Argea Prima spill in Puerto Rico[47] and the Witwater spill in the Canal Zone.[60] Damages to salt marsh communities have occurred as a result of the Chryssi P. Goulandris spill in Milford Haven,[24] the Arrow spill in Chedabucto Bay,[43] and the West Falmouth spill in Massachusetts.[30]

Experimental attempts are now being made in the field to evaluate the effects of oil, mostly on salt marsh communities. After artificially oiling a natural estuarine tidal pond, Lytle[38] reported reduction in productivity of marsh plants, drastic changes in diversity and density of fish populations, and imbalances between numbers of zooplankton and phytoplankton as a result of the initial impact of the oil. After surveying marsh grass communities around refineries, and areas that were artificially oiled, Baker[61] noted that marsh grasses recovered well from a single spill, but that continuous or repeated exposure could be harmful. Particularly sensitive were shallow-rooted plants with little or no food reserves, in comparison to perennials with large food reserves and resistant characteristics at the cellular level.

Oil has a tendency to persist in shallow estuarine sediments,

e.g., after the West Falmouth spill, which may prolong toxic effects and delay recovery. However, in many cases once the oil has been removed recovery may occur at a moderate rate--few to several years. This is because estuarine organisms typically are "r-strategists," i.e., they reproduce and grow to maturity rapidly;[18] and secondly, similar to many intertidal species, these shallow water inhabitants have to some extent developed resistant adaptations to cope with inconsistencies in the physical environment. On the other hand, if Copeland's[21] "response to disturbance" model is true then some of the more diverse and complex communities, particularly those in tropical mangrove swamps, may reveal slower rates of recovery. Mangroves are particularly vulnerable to clogging or interference with the holes in their aerial root system.[62] Odum and Johannes[62] point out that mangrove trees generally require a minimum of twenty years to recover.

Coral Reefs.--The threat of contaminating coral reefs with oil is increasing. While a complex of refineries continues to discharge effluents over reefs along the South coast of Puerto Rico,[63] offshore drilling has begun in the vicinity of Indonesia, and exploration for oil has commenced on the Great Barrier Reef of Australia.[4] Yet, little is known of the ecological effects of oil on coral reef communities.[4,64]

Several examples summarize much of what is known. Following the Witwater spill in the Canal Zone in 1968, a qualitative survey was conducted to assess the impact on the coral community.[60] However, no evidence was found suggesting that severe damages had occurred. On the other hand, Cerame-Vivas et al.[65] noted that the discharge of refinery wastes along the South coast of Puerto Rico caused structural changes in a nearby coral community. Likewise, during field experiments, Birkeland et al.[66] found that hermatypic corals exposed to Bunker C showed reduced and varied growth between heads. The latter finding was significant in the sense that a coral's success in the community--ability to tolerate grazing and predation, and to compete for space--is dependent largely upon its growth.[67] Johannes et al.[68] have found that oil damages corals while they are exposed to air.

Coral reef communities are extremely complex and are characterized by high diversity.[19,20,21] If Copeland's[21] "response to disturbance" model is true, then coral reef communities would be relatively unstable in response to oil. Initial impacts from oil may be great and recovery may be extremely slow. Without conclusive data, such a statement is strictly conjectural at this time. However, Copeland[21] reviewed several incidents, revealing that coral communities respond drastically to either dredge spoils, turbidity, or organic loading.

Polar Ecosystems.--There is a paucity of information concerning effects of oil in polar regions.[69,70] This is a serious inadequacy since it is generally conceded that oil spilled in polar waters will have severe and long-lasting ecological effects.[69,71] Reasons include: 1) polar organisms have slow growth rates, extended life cycles,

longer reproductive periodicity, and narrow ranging dispersal stages;[72,73] and 2) at low temperatures, one might expect a slow rate of dispersion and biological degradation of the oil.[74]

Such a conjecture may apply well to the more environmentally constant polar areas--self contained arctic lakes[75] or the bottoms of deep bodies of water. Yet, application to some low-diversity, coastal polar communities, existing under extreme conditions (variable temperatures, exposure to ice, shifts in periods of light and darkness), is questionable since theoretically[21] these communities may already have adapted to harsh, natural conditions in such a way that the effects from additional disturbances may be minimized.

CONCLUSIONS

Analysis of available data from bioassays conducted on the adult stages of a wide variety of marine organisms reveals lethal effects of soluble aromatic hydrocarbon fractions in the 1 to 100 part per million range. For the more sensitive larval and juvenile forms, lethal effects may occur at lower levels, typically between 0.1 and 1 ppm. Major sublethal responses of commercially or ecologically important species (e.g., certain shellfish) are noted in the low part per billion range, i.e., between 1 and 10 ppb.

We have learned that basic biological differences exist between various populations and communities of organisms or between major ecosystem types. We also suspect that due to such differences, various populations, communities or ecosystems are not the same in their susceptibility to or ability to recover from effects of oil. However, it must be stressed that data are not available at this time to provide a sufficient basis for accurately distinguishing varying degrees of response to oil. One must recognize that predicted responses according to population, community or ecosystem type, that are summarized herein, are subject to uncertainty.

However, based on data collected thus far, strict control is suggested for oil development and related activities in certain highly productive, continental shelf regions, and in wetlands and estuaries, where ecologically and commercially important species seek shelter, food and breeding grounds. Soft-bottom, coastal benthic communities are vulnerable to impact, and recovery from spilled oil could be relatively slow where oil tends to persist or where community stability is extremely low. Bird populations are highly susceptible to lethal and adverse effects, if contact with oil occurs. Local breeding populations of many organisms (including ichthyoplankton and meroplankton) may become heavily impacted, especially in certain confined coastal areas. In many cases, populations and/or communities of pelagic fish, mammals, phytoplankton, and zooplankton are considered low risk in terms of susceptibility to effects of petroleum. Fish and mammals are highly mobile and can thus usually avoid spills. If populations of plankton

happen to encounter a floating slick in open waters, and individuals are eliminated, densities and age-distributions are generally quickly restored through effective reproductive and dispersal mechanisms. Little is known of the ecological effects of petroleum on neuston or in coral and polar ecosystems.

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SIVA: I think we all agree that we have come a long way from the LD_{50} static bioassay but I think, also, that you must agree that that was definitely the place we had to start. We all definitely need information on effects of oil on total ecosystems. To me, the only way to get this information, since we have our spills in areas where we haven't had very good baseline data previously, is to study a system and then experimentally spill oil in it.

I would like your opinion of that approach. What would be your approach to the problem and what is EPA doing along this line to get a handle on total ecosystem effects?

SCHNEIDER: As far as the types of studies to be done presently, as I mentioned, the large marine ecosystem work that we are doing is now aimed at chronic effects instead of individual spills.

That is the work being done in our large tanks at the University of Rhode Island, and it really isn't URI that is doing it. A large number of workers everyplace from Woods Holes to Skidaway Institute is included. We are pushing microcosm experiments done on a fairly large and grand scale. The tanks are 25 or 30 feet high, 8 feet in diameter, complete with a benthic community and running a semi-flow-through arrangement.

We are using as our baseline, in this case, Narragansett Bay as a whole. The first thing we are doing is tuning our microcosms, as we have done on the smaller ones already, to existent systems in the Bay; then when we understand and recognize that our microcosms are mimicking natural systems, so we feel free to dose them.

Initially, we are going to be dosing at the 100-part-per-million range. As far as spilled oils are concerned, we have done, and we have funded, and we are still carrying out spilled oil experiments in controlled systems, and I think that they are very important. The main things to look for here are the recovery of those systems. How rapidly do they get back to their individual structural and functional relationships that have existed?

I think terrestrial ecologists and aquatic ecologists have expended an immense amount of money in individual experiments trying to look at complex interactions. Ecosystems study should be done in a holistic manner -- looking at total systems parameters, rather than individual species parameters within that.

TABLE 1

SOURCES OF PETROLEUM IN THE MARINE ENVIRONMENT[a]

	Natural	Intentional	Accidental
Natural Seeps	10%		
Offshore Production			1%
Transportation			
LOT tankers		5%	
Non-LOT tankers		13%	
Dry docking		4%	
Terminal operations			
Bilges bunkering		8%	
Tanker accidents			3%
Non-tanker accidents			2%
Coastal Refineries		3%	
Atmosphere		10%	
Coastal Municipal Wastes		5%	
Coastal (nonrefining industrial wastes)		5%	
Urban Runoff		5%	
River Runoff		26%	
Total	10%	84%	6%

[a]Recalculated from National Academy of Sciences.[5]

TABLE 2

SUMMARY OF LETHAL TOXICITY[a]

Class of Organisms	Estimated Conc. (ppm)[b] of S.A.D.[c] Causing Toxicity	Estimated Amount (ppm) of Various Petroleum Substances Containing Equivalent Amounts of S.A.D.				
		#2 Fuel Oil (Est. Max. % S.A.D. = 1-30)	Crude Oil (Est. Max. % S.A.D. = 0.1-10)	Kerosene (Est. Max. % S.A.D. = 1-20)	Dispersant (BP 1002) (Est. Max. % S.A.D. = 1-20)	Residual (Est. Max. % S.A.D. = 0-1)
Flora	10-100	50-500	10^4-10^5	10^2-10^3	10^2-10^3	10^3-∞ (no effect)
Finfish	5- 50	25-250	10^4-10^5	50-500	50-500	500-∞
Larvae (all species)	0.1-1.0	0.5- 5	10^2-10^3	1- 10	1- 10	10-∞
Pelagic Crustaceans	1- 10	5- 50	10^3-10^4	10-100	10-100	10^2-∞
Gastropods	10-100	50-500	10^4-10^5	10^2-10^3	10^2-10^3	10^3-∞
Bivalves	5- 50	25-250	10^4-10^5	50-500	50-500	500-∞
Benthic Crustaceans	1- 10	5- 50	10^3-10^4	10-100	10-100	10^2-∞
Other Benthic Organisms (Polychaetes, etc.)	1- 10	5- 50	10^3-10^4	10-100	10-100	10^2-∞
Birds		← Coating →				

[a] Adopted with modifications from Moore.[2]

[b] Based on a review of the literature by Moore et al.[1] and their estimates of S.A.D. in the bioassay solutions.

[c] Soluble aromatic hydrocarbon derivatives (mono- and dicyclic aromatics, naptheno-aromatics).

TABLE 3

SUMMARY OF SOME SUBLETHAL EFFECTS OF PETROLEUM PRODUCTS ON MARINE ORGANISMS[a]

Type of Organism	Species	Reference	Type Petroleum Product	Concentration	Sublethal Response
Marine Flora	Marsh Plants (Festuca rubra, Distichlis maritima)	Baker, in Cowell, 1971[76]	Crudes and refinery effluents.	Single or successive coatings with crude.	Inhibition of germination and growth. Repeated coatings cause disappearance of some plants (increasing order of tolerance: shallow rooted plants, shrubby perennials, filamentous green algae, perennials, perennials with large food reserves).
	phytoplankton (Chlorella vulgaris; Chlamydomonas angulosa)	Kauss, et al., 1973[77]	Crude Naphthalene	1 ppm 3 ppm	Suppress growth. Reduction of bicarbonate uptake (i.e., photosynthesis).
	phytoplankton (diatoms and dinoflagellates)	Mironov, 1970[7]	"Oil"	10^{-1} 10^{-4} ppm	Inhibition or delay in cellular division.
	phytoplankton (Asterionella japonica)	Aubert et al., 1969[78]	Kerosene	3 ppm; 38 ppm	Depression of growth rate.
	phytoplankton (Phaeodactylum tricornutum)	Lacaze, 1967[79]	Kuwait crude	"1 ppm"	Depression of growth rate

[a]Adopted with updated modifications from National Academy of Sciences.[5]

TABLE 3 Continued

Type of Organism	Species	Reference	Type Petroleum Product	Concentration	Sublethal Response
Marine Flora Continued	phytoplankton (Monochrysis lutheri)	Strand et al., 1971[80]	Kuwait crude; dispersant emulsions	20-100 ppm	Inhibition of growth; reduction of bicarbonate uptake at 50 ppm.
	phytoplankton (Phaeodactylum tricornutum, Skeletonema costatum, Chlorella sp., Chlamydomonas sp.	Nuzzi, 1973[81]	Extracts of outboard motor oils, No. 6 Fuel Oil, No. 2 Fuel Oil.	1 ppm	Inhibition of growth with No. 2-stimulation with No. 6 and outboard motor oil.
	phytoplankton (mixed natural samples)	Gordon and Prouse, 1973[82]	Venezuelan crude, No. 2 and 6 Fuel oils.	10-200 mg/ℓ (ppm)	Stimulation of photosynthesis at 10-30 µg/ℓ, decrease in photosynthesis at 100-200 µg/ℓ No. 2 fuel oil.
	kelp (Macrocystis angustifolia)	Wilber, 1969[83]	Toluene	10 ppm	75% reduction in photosynthes within 96 hr.
	lichen (Lichen pygmaea)	Brown, 1972[84]	Kuwait crude, BP 1002	0.1-100 ppm	1 ppm emulsifier decrease tot. C^{14} fixation.
	Spartina marsh grass	Lytle, 1975[38]	Crude	Poured into pond.	Decrease in productivity.
	Algae (Ulva lactuca, Grateloupia dichotoma, Polysiphonia opaca)	Davavin et al., 1975[85]	Crude	.1-10 mℓ/ℓ (100-10,000 ppm)	Complete inhibition of biosynthesis of DNA and RNA at higher conc. for Ulva.

[a]Adopted with updated modifications from National Academy of Sciences.[5]

TABLE 3 Continued

Type of Organism	Species	Reference	Type Petroleum Product	Concentration	Sublethal Response
Larvae and eggs	Pink Salmon fry (Onchorhynchus gorbuscha)	Rice, 1973[86]	Prudhoe Bay crude	1.6 ppm	Avoidance effects; could have effect on migration and behavior.
		1975[87]	Prudhoe Bay crude	0.73 ppm	Decrease in growth
	Black sea turbot (Rhombus maeoticus)	Mironov, 1967[8]	"Oil"	0.01 ppm	Irregularity and delay in hatching--resulting larvae deformed and inactive.
	Plaice larvae (Pleuronectes platessa)	Wilson, 1970[88]	BP 1002	0-10 ppm	Disruption of phototactic and feeding behavior.
	Cod fish larvae (Gadus morhua)	Kühnhold, 1970[89]	Iranian crude	Aqueous extracts from 10^3 ppm, 10^4 ppm	Adverse effect on behavior leading to death.
	Lobster larvae (Homarus americanus)	Wells, 1972[90]	Venezuelan crude	6 ppm	Delay molt to 4th stage.
	Sea Urchin larvae (Strongylocentrotus purpuratus)	Allen, 1971[91]	Extracts of Bunker C	0.1-1 ppm	Interference with fertilized egg development.
	Barnacle larvae (Balanus)	Mironov, 1970[7]	"Oil"	10-100 µℓ/ℓ (ppm)	Abnormal development.
	Crab larvae (Pachygrapsus marmoratus)	Mironov, 1970[7]	"Oil"	10-100 µℓ/ℓ (ppm)	Initial increase in respiration.

[a]Adopted with updated modifications from National Academy of Sciences.[5]

TABLE 3 Continued

Type of Organism	Species	Reference	Type Petroleum Product	Concentration	Sublethal Response
Larvae and eggs (Continued)	Polychaete larvae (Sabellaria spinulosa)	Smith, 1968[35]	BP 1002	0.5-1 ppm	Abnormal irritability in larval revealed by stiffening out of median setae.
	Oyster larvae (Ostrea edulis)	Simpson, 1968[92]	BP 1002	1 ppm	Inhibition of growth
	Herring larvae (Clupea harengus)	Kühnhold, 1969;[93] 1971[94]	Crude	5 ppm	High % deformed larvae (stunted tail and constricted yolk mass) among hatching eggs; normal hatched larvae became narcotized within 2 days after hatching and died by 3rd.
	Herring and anchovy larvae (Clupea pallasi; Engraulis mordax)	Struhsaker, et al., 1974[95]	Benzene	15-45 ppm	35-45 ppm causes delay in development of eggs and produces abnormal larvae; 10-35 ppm causes delay in development of larvae; decrease in feeding and growth, and increase in respiration.
Fish	Chinook salmon (Onchorhynchus tshawytscha, striped bass (Morone saxatilis)	Bracksen and Bailey, 1973[96]	Benzene	5, 10 ppm	Initial increase in respiration.
	Menidia menidia	Gardner, 1975[97]	Crude (whole fractions) (water-soluble) (water-insoluble)	140 ppm (v/v) 12 ppm estimated 588 ppm (v/v)	Histological damage to chemoreceptors.
	Cyprinodon variegatus, Lagodon themboides, Micropogon undulatus	Steel and Copeland, 1967[98]	Petrochemical wastes	0.2-2.0 ppm in addition to 0.4-4.0 phenol	Respiratory inhibition.

[a]Adopted with updated modifications from National Academy of Sciences.[5]

TABLE 3 Continued

Type of Organism	Species	Reference	Type Petroleum Product	Concentration	Sublethal Response
Fish (Continued)	Lagodon rhomboides	Wohlschlag and Cameron, 1967[99]	Petrochemical wastes	50% of wastewater	Respiratory inhibition.
	Ictalurus natalis	Todd, 1972[100]			Alteration of social behavior.
	Menidia menidia	Gardner et al., 1975[101]	Waste motor oil	>20 ppm	Incidence of lesions in vascular systems (pseudobranch, heart, arterial system).
	Siganus rivulatus	Eisler, 1975[102]	Dispersant Crude	.010 mℓ/ℓ (10 ppm) .3-10 mℓ/ℓ (300-10,000 ppm)	Reduction in blood hematocrit. Increase in somatoliver index.
Crustaceans	Lobster, (Homarus americanus)	Blumer et al., 1973[103]	Crude, Kerosene	10 ppm	Effects on chemoreception, feeding times, stress behavior, aggression, grooming.
	Barnacle, (Pollicipes polymerus)	Straughan, 1971[29]	Crude--Santa Barbara	Field study after blowout	Apparent decrease in adult brooding; no recruitment in oiled areas.
	Lobster (H. americanus)	Atema and Stein, 1972,[56] 1974[57]	LaRosa Crude	Extracts; whole oil at 1:100,000 (10 ppm)	Delay in feeding with whole crude fractions.
	Crab, (Pachygrapsus crassipes)	Kittredge, 1971[104]	Crude	Dilutions of diethyl ether extracts (1:100)	Inhibition of feeding.
	Crab, (Uca pugnax)	Krebs, 1973[105]	No. 2 Fuel oil	Field observations after W. Falmouth spill	Adverse effects on sexual behavior. Mortalities in heavily-oiled areas.

[a]Adopted with updated modifications from National Academy of Sciences.[5]

TABLE 3 Continued

Type of Organism	Species	Reference	Type Petroleum Product	Concentration	Sublethal Response
Crustaceans (Continued)	Copepod (Calanus helgolandicus)	Spooner and Corkett, 1974[106]	Suspended oil droplets in lab vessels	10 ppm	Decrease in feeding and metabolic activity among survivors, based on amount fecal pellets deposited by controls vs. experimentals.
	Benthic amphipods (Gammarus oceanicus, Onisimus affinis) isopod (Mesidotea entomon)	Percy, 1976[107]	3 Crudes	Oil-soaked object; oil tainted food	Avoidance of oil masses and oil-tainted food for amphipods; neutral response for isopod.
	Crab, (Pachygrapsus crassipes)	Kittredge et al., 1975[10]	Naphthalene	1 ppb	Inhibition of feeding (reduction in intensity of response)
			Crude	(extracts)	Inhibition of feeding and response to sex pheromone (male mating stance).
Molluscs	Mussel (Mytilus edulis) Modiolus demissus	Gilfillan, 1973,[108] 1975[109]	Crude	1 ppm	Reduction in carbon budget (increase in respiration; decrease in feeding and assimilation).
	Snail (Nassarius obsoletus)	Blumer et al., 1973[103]	Kerosene	Saturated extract diluted 10^{10}	40% reduction in chemotactic perception of food.
	Snail (Nassarius obsoletus)	Jacobson and Boylan, 1973[9]	Kerosene	0.001-0.004 ppm	Reduction in chemotactic perception of food.
	Clam (Mya arenaria)	Barry and Yevich, 1975[14]	No. 2 Fuel oil	Collected from field	Gonadal tumors.

[a]Adopted with updated modifications from National Academy of Sciences.[5]

TABLE 3 Continued

Type of Organism	Species	Reference	Type Petroleum Product	Concentration	Sublethal Response
Molluscs (Continued)	Oyster (Crassostrea virginica)	Mackin and Hopkins, 1961[110]	Bleedwater	Spray	Reduced growth and glycogen content.
	Snail (Littorina littorea)	Perkins, 1970[111]	BP 1002	30 ppm	Significant inhibition to growth.
	Oyster (Crassostrea virginica)	Menzel, 1948;[55] in Nelson-Smith, 1973[3]	"Oil"	0.01 ppm	Marked tainting.
	Mussel (Mytilus edulis)	Blumer et al., 1971	No. 2 Fuel oil	Collected from field after spill.	Inhibition in development of gonads.
	Gastropod drill (Drupa granulata), Mussel (Mytilus variabilis)	Eisler, 1973[112]	Iranian crude, dispersant	10 mℓ/ℓ (10,000 ppm)	Decrease in predation rate of drill on mussel when exposed to crude; decrease in fecundity of drills when exposed to dispersant.
	Oyster (Crassostrea virginica), Scallop (Aquipectins irradians)	Gardner et al., 1975[101]	Waste motor oil	> 20 ppm	Incidence of lesions in branchial efferent vein, mantle, and gastro-intestinal tract of oyster; and in mantle, gill, and kidney of scallop.
	Mussel (Mytilus variabilis)	Eisler, 1975[102]	Dispersant Iranian crude	.020 mℓ/ℓ (20 ppm) 3 mℓ/ℓ (3000 ppm)	Decrease in ability to attach to surfaces
	Mussel (Mytilus edulis)	Gonzalez et al., 1976[11]	No. 2 Fuel oil, water-accommodated-fractions	10 ppb- 1 ppm	Decrease in filter feeding activity; and byssal thread attachment at the higher concentrations.

[a]Adopted with updated modifications from National Academy of Sciences.[5]

TABLE 3 Continued

Type of Organism	Species	Reference	Type Petroleum Product	Concentration	Sublethal Response
Molluscs (Continued)	Oyster (Crassostrea virginica)	Kittredge et al., 1975[10]	Naphthalene	1 ppm	Irritation of gill cilia.
	Snail (Littorina littorea)	Hargrave and Newcombe, 1973[113]	Bunker C, dispersant	.750-80 ppm	Increase in crawling and respiration rates (decreased in response to undefined conc. of dispersant or dispersant plus oil).
Other Benthic Invertebrates	Polychaeta (Capitella capitata)	Bellan et al., 1972[12]	Detergent	0.01-10 ppm	Decrease in survival, fecundity.
	Octocoral (Heteroxenia fuscescens)	Eisler, 1975[102]	Crude	10 mℓ/ℓ (10,000 ppm)	Reduction in tentacular pulsation.
	Hermatypic corals (Porites furcata)	Birkeland and Reimer, 1976[66]	Bunker C, diesel	exposed to oil layer	Exposure caused decrease in growth and variation of heads.
	Corals (Pavonia, Psammocora, Porites)	Reimer, 1975[114]	Bunker C, diesel	exposed to oil layer	Caused prolonged "mouth opening" responses, followed by reduction in feeding.

[a]Adopted with updated modifications from National Academy of Sciences.[5]

TABLE 4

SUMMARY OF EFFECTS OF OIL ON POPULATIONS AND COMMUNITIES

Community or Population Type	Expected Degree of Initial Impact		Expected Recovery	
Plankton	Light to Moderate:	Impact dependent on chance event of contacting floating slick. Decrease in population densities may have effect on local productivity. Greatest danger to small local breeding populations composed of larval fish.	Fast to Moderate:	Effective reproductive and dispersal mechanisms for most phyto- and zooplankton in open waters (populations dense, widely dispersed; individuals ubiquitous, prolific, grow quickly to maturity). Local breeding populations of larval fish and shellfish may take much longer to recover.
Neuston	Unknown:	Chance of contact high since communities exist on or near surface. Contamination reported, but effects unknown.	Unknown:	Ecology poorly understood.
Benthic Communities		Mortalities lead to decrease in population densities and age distributions; changes in species abundance and distribution; imbalances between interacting populations.		
Rocky Intertidal	Light: (with exceptions, e.g., Tampico Maru spill)	Hardiness of organisms. Most damage from coating leading to suffocation or loss of purchase on substrates.	Fast:	Oil rapidly removed by waves. Populations rapidly restored since individuals grow and reproduce rapidly.
Sandy or Muddy Intertidal	Moderate:	Impact increased by persistence of oil in unconsolidated substrates. Chance for greater mortalities since infaunal organisms may be more sensitive than rocky intertidal organisms that have developed defense mechanisms for living in rigorous and variable environments.	Moderate:	Persistence of oil in sediments prolongs toxic effects.